Thermal Performance of Residential Electric Water Heaters Using Alternative Blowing Agents

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ABSTRACT

This paper presents the results of a study designed to quantify the performance of water heaters insulated with polyurethane foams using three different blowing agents—hydrochlorofluorocarbon R-141b, H_2O/CO_2, and hydrofluorocarbon R-245fa. The thermal conductivity of the foam was measured, as a function of mean temperature, using a guarded hot plate apparatus. Electric residential water heaters, insulated with the three polyurethane foams, were tested to determine the influence of the blowing agent on the water heater's energy factor and overall heat loss area coefficient. A relationship between the overall heat loss area coefficient and energy factor was developed and compared to experimental results. An infrared imaging system revealed that areas surrounding the heating element access covers, the lower circumference of the water heater, and piping penetrations were significantly higher in temperature than the exterior surface of the water heater.

INTRODUCTION

In the 1970s, polyurethane foam began replacing glass fiber in residential water heaters. Due to its lower thermal conductivity (compared to glass fiber), manufacturers were able to improve the energy efficiency of water heaters without increasing the exterior dimensions. Additionally, foam insulation provided structural benefits and simplified the manufacturing process. For many years, the blowing agent used to produce the polyurethane foam insulation for water heater applications was the fully halogenated chlorofluorocarbon R-11.

The discovery that continued use of chlorofluorocarbons would have a severe impact on the ozone layer resulted in the enactment of the 1987 Montreal Protocol. The Montreal Protocol stipulated that fully halogenated chlorofluorocarbon products, used as blowing agents in the manufacture of polyurethane foams, could not be produced after January 1, 1996. Consequently, an alternative blowing agent, hydrochlorofluorocarbon R-141b became accepted for the manufacture of water heaters. Compared to an ozone depletion potential of 1.0 for R-11, the ozone depletion potential of 0.1 associated with R-141b was a significant improvement.

The blowing agent R-141b is considered a transitional blowing agent in the United States and will be phased out on January 1, 2003. The search for blowing agents with zero ozone depleting potential has lead to a number of candidates including hydrofluorocarbon R-245fa as a blowing agent and the addition of water to the foam formulation. The addition of water reacts with isocyanate, forming CO_2. In this paper the use of water to produce CO_2 as the blowing agent will be denoted as H_2O/CO_2. In the United States it appears that R-245fa has emerged as a leading candidate to replace R-141b in the appliance industry (Albouy et al. 1997; Logsdon et al. 1997). However, delays in the decision to build a manufacturing plant to produce R-245fa may force the water heater industry to use H_2O/CO_2 as the blowing agent.

In addition to environmental considerations, the selection of a blowing agent to replace R-141b must also consider the thermal performance of the polyurethane foam. Residential water heaters sold within the United States must meet the current and future energy efficiency standards as specified by the Department of Energy (CFR 1998).

This paper presents the results of a study that explored the impact of two proposed blowing agents on the performance of residential water heaters. The study includes a comparison of

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the polyurethane foam's thermal conductivity resulting from the use of blowing agents R-141b, R-245fa, and H_2O/CO_2. Three sets of four water heaters were manufactured using each of the three blowing agents. The water heaters were tested to determine their overall thermal integrity and thermal efficiency. The results of this study should help water heater manufacturers select an appropriate blowing agent.

TEST SPECIMEN DESCRIPTION

Commercially available electric residential water heaters were selected for this study. The water heaters have a nominal capacity of 189 L (50 gal) and contain two electrically interlocked 4500-watt heating elements. Normal production units contain approximately 51 mm (2.0 in.) of polyurethane foam between the side and top of the storage tank and the exterior metal jacket. Glass-fiber insulation, approximately 25 mm (1 in.) thick, is positioned between the storage tank's bottom and exterior metal jacket. Twelve of these units, without the polyurethane foam, were manufactured and forwarded to a polyurethane foam supplier.

The polyurethane foam supplier subsequently insulated four water heaters and produced three sets of foam block specimens, with each set blown with one agent, R-141b, H_2O/CO_2, and R-245fa. The foam block specimens' size, 660 mm × 660 mm × 66 mm (26 in. × 26 in. × 2.6 in.), was chosen to be compatible with the guarded hot plate apparatus. Each polyurethane foam's formulation and production date are documented in Table 1. Production dates were selected such that the elapsed time between the date of manufacture and testing were approximately equal, 28 days, for each foam formulation.

EXPERIMENTAL APPARATUS

One-Meter Guarded Hot Plate

The thermal conductivity of the foam specimens was measured using a one-meter guarded hot-plate (Powell and Rennex 1983; Zarr and Hahn 1995), as shown in Figure 1. The apparatus has been used to develop standard reference materials that permit industry, academia, and government laboratories to calibrate their "in-house" instrumentation and provide traceability to national and international standards. The main components of the apparatus are a guarded hot-plate and two isothermal cold surface plates (Figure 2). The guarded hot-plate includes a metering section used to measure the heat flow into the test specimens and a guard section to minimize heat flow from the metering section in the radial direction. Guarding at the edges of the specimens is provided by an environmental chamber maintained at the mean temperature of the hot and cold plates. For this study, the apparatus was operated in the double-sided mode of operation; that is, two specimens produced with each of the three blowing agents are positioned between the hot plate and cold plates. The thermal conductivity measurement represents the average of the two specimens.

TABLE 1
Polyurethane Foam Formulations

Blowing Agent	HCFC-141b	H_2O/CO_2	HFC-245fa
Isocyanate blend "A" parts by weight	1	1	1
Polyol blend "B" parts by weight	1	0.65	0.81
Blowing agent percentage (%)	22.8	5.9	24.3
Polyol temperature, °C (°F)	26.7 (80)	23.9 (75)	22.8 (73)
Isocyanate temperature, °C (°F)	26.7 (80)	23.9 (75)	22.8 (73)
Cream time, s (s)	5	7	---
Gel time, s (s)	46	53	49
Tack free time, s (s)	102	150	69
Free rise density, kg/m^3 (lb/ft^3)	23.68 (1.48)	24.0 (1.50)	23.4 (1.46)
Molded density, kg/m^3 (lb/ft^3)	32.00 (2.00)	32.5 (2.03)	32.3 (2.02)
Production date	4/21/98	6/2/98	7/8/98

Residential Water Heater Test Facility

A laboratory (Fanney 1990; Fanney and Dougherty 1996), dedicated to the evaluation of residential water heaters, was used to measure each water heater's energy factor and overall heat loss area coefficient (Figure 3). The water heater under evaluation is placed on a platform with piping connections in accordance with the Department of Energy's (DOE) *Test Procedures for Residential Water Heaters* (*Federal Register* 1998). Thermocouples measure the water temperature entering and leaving the water heater, the temperature of the water within the water heater at six specified locations, and the surrounding ambient temperature. A weigh tank, positioned on a load cell, captures the water withdrawn from the storage tank during each of the six hot water draws. A digital power analyzer measures the energy consumed by the water heater.

The output signals of the thermocouples, load cell, and digital power analyzer are recorded using a computer-controlled data acquisition system. Every 30 seconds, the output signal of each transducer is measured, converted to engineering units, and calibration corrections applied. The results are displayed on the computer's monitor and archived to a floppy diskette. During the removal of heated water, the output signals of inlet and outlet thermocouples and the load cell are measured, converted to engineering units, corrected, and recorded every three seconds.

The computer-controlled data acquisition system also controls the opening and closing of two solenoid valves. Two minutes prior to removal of heated water, a solenoid valve

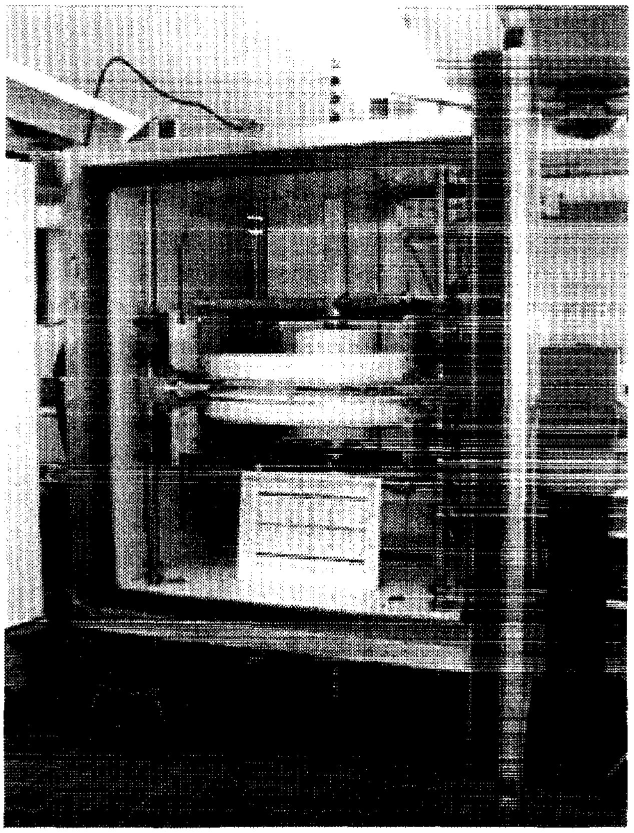

Figure 1 One-meter guarded hot plate.

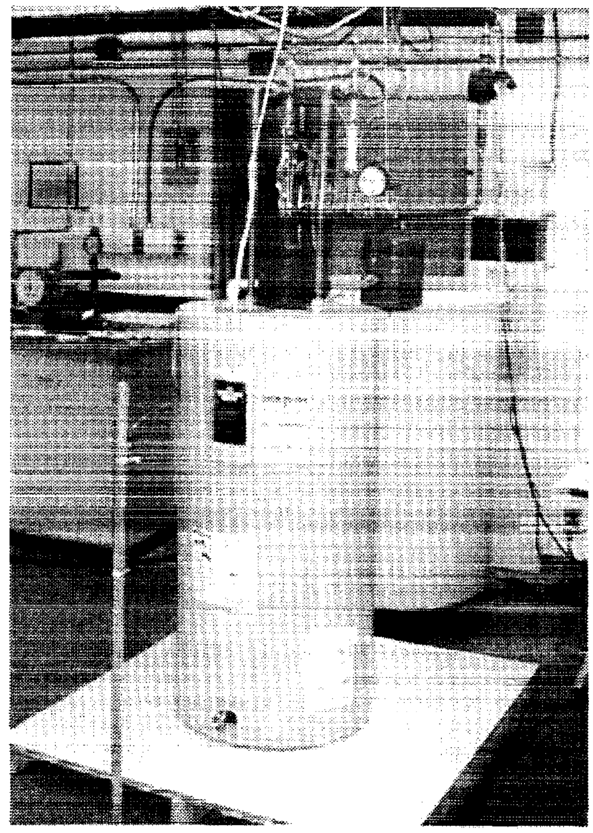

Figure 3 Residential water heater laboratory.

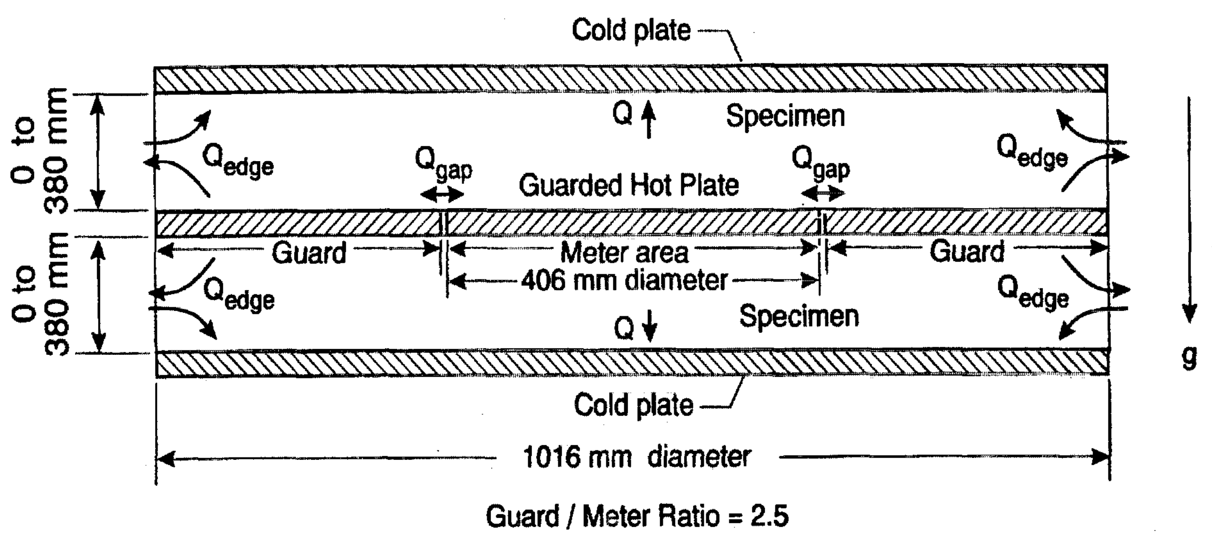

Figure 2 Schematic of one-meter guarded hot plate.

positioned at the discharge of the weigh tank is closed. Thirty seconds prior to the removal of heated water, the load cell is used to measure the tare weight of the weigh tank. At the prescribed times, the discharge pipe's solenoid valve is opened and the draw commences. The draw continues until the output signal of the load cell indicates that the desired quantity of heated water has been removed. The solenoid valve on the discharge pipe is closed, a final measurement of the load cell is made, and the weigh-tank solenoid valve is opened to release the captured water.

The apparatus used to measure the overall heat loss area coefficient is similar to that used to measure the energy factor. Unlike the energy factor apparatus, however, the weigh tank, load cell, and associated solenoid valves are not present. Every 10 minutes, the computer interrogates the digital power analyzer and data acquisition system to update the quantity of energy consumed by the water heater and measure the output signals of the six thermocouples within the storage tank and the ambient thermocouple. The output signals are subsequently converted to engineering units, corrected in accordance with calibration data, displayed on the computer's monitor, and archived to a floppy diskette.

A water-conditioning loop provides supply water at the prescribed temperature during tests to measure the water heater's energy factor. The water-conditioning loop consists of three 303 L (80 gal) storage tanks connected in series, an external chilled water-to-water heat exchanger, immersion heaters within the storage tanks, pumps, and an electronic temperature controller. The pumps are used, in conjunction with a fluid loop, to continuously circulate conditioned water past a pipe that supplies water to the water heater. The water conditioning loop allows the inlet water temperature to be varied from approximately 5°C (41°F) to 60°C (140°F). During this study, the inlet fluid conditioning loop supplied water at approximately 14.4°C (58°F) in accordance with DOE's *Test Procedure for Residential Water Heaters* (*Federal Register* 1998).

An infrared thermography system was used to determine if there were any voids in the water heater's insulation system. An image of the water heater's surface temperature identified any voids in the insulation between the storage tank and the outer metal jacket. It also identified areas of heat loss resulting from piping penetrations through the water heater's outer jacket or other high thermal conductance paths.

TEST PROCEDURES AND CONDITIONS

Thermal Conductivity Measurements

Measurements of thermal conductivity[1] of the foam specimens were determined in accordance with ASTM Test Method C 177 (ASTM 1997). With proper guarding in the lateral direction, the guarded hot plate is designed to provide one-dimensional heat flow (Q) through the specimen pair. Under steady-state conditions, the thermal conductivity of the specimen pair was determined using Equation 1.

$$\lambda = \frac{QL}{A\Delta T} \tag{1}$$

where

λ = thermal conductivity, W/m °C (Btu · in./h · ft²·°F)

Q = rate of heat flow through the meter area of the specimens, W (Btu/h)

A = meter area normal to direction of heat flow, m² (ft²)

ΔT = $T_h - T_c$, temperature difference across specimens, °C (°F)

T_h = hot plate temperature, °C (°F)

T_c = cold plate temperature, °C (°F)

L = thickness of specimens measured in situ, m (in.)

Each pair of specimens was measured as received (i.e., no surface preparation was required). The hot and cold plate temperatures were selected to subject the foam specimens to temperature levels that would simulate a residential water heater application. The cold plates for all tests were maintained near the ambient temperature specified by the DOE's *Test Procedures for Residential Water Heaters* (*Federal Register* 1998), 19.7°C (67.5°F). The hot plate was maintained at nominal temperatures of 51.7°C (125°F), 57.2°C (135°F), and 62.8°C (145°F) for tests 1, 2, and 3, respectively. The hot plate temperatures were selected in an attempt to bracket the temperature range that the warm side of the insulation would be subjected to in a water heater application with thermostats set at 57.2°C (135°F) (*Federal Register* 1998). The tests were conducted once at each temperature, generally in one to two days. During testing, dry air was continuously injected into the environmental chamber maintaining the relative humidity at 15% or less.

Bulk Density Measurements

The bulk densities (ρ) of the foam specimens were determined by dividing the mass of the specimen by its volume (V), or

$$\rho = \frac{m}{V} \tag{2}$$

where

ρ = specimen density, kg/m³ (lb/ft³);

m = specimen mass, kg (lb);

V = specimen volume, m³ (ft³).

The mass was obtained by using a precision balance having a sensitivity of 0.1 g. The dimensions of the specimens were measured using a steel rule having a resolution of 0.5 mm

[1] The thermal transmission properties of heat insulators determined from standard test methods typically include several mechanisms of heat transfer, including conduction, radiation, and possibly convection. For that reason, some experimentalists will include the adjective "apparent" when describing thermal conductivity of thermal insulation. However, for brevity, the term *thermal conductivity* will be used in this paper.

(0.02 in.). The thickness of the specimen was averaged from five measurements taken on a granite flat table with a precision caliper, 0.1 mm (0.004 in.) resolution.

Energy Factor Measurements

The energy factors for each water heater were measured using the DOE's *Test Procedures for Residential Water Heaters* (*Federal Register* 1998). During the 24-hour test period, a total of 243.4 L (64.3 gal) are removed from the water as a result of six equal draws. The draws take place at one-hour intervals during the first six hours of the test. Upon completion of the sixth draw, the water heater remains in a standby mode until 24 hours have elapsed.

The thermal efficiency of a water heater can be expressed as

$$\eta_{th} = \frac{Q_{hw}}{Q_{in} + \frac{Q_{stored}}{\eta_r}} \qquad (3)$$

where

Q_{hw} = quantity of energy removed from the water heater, MJ (Btu),

Q_{in} = total electrical energy consumption, MJ (Btu),

Q_{stored} = change in the water heater's stored energy, MJ (Btu),

η_r = 0.98, the assumed recovery efficiency for electric water heaters (*Federal Register* 1998).

The Q_{in} term in Equation 3 may be expanded such that thermal efficiency is expressed as

$$\eta_{th} = \frac{Q_{hw}}{\frac{Q_{hw} + Q_1 + Q_{stored}}{\eta_r}} \qquad (4)$$

where

Q_1 = heat loss from the water to the surrounding ambient, MJ (Btu).

Energy factor is defined the same as thermal efficiency except that the quantities Q_{hw} and Q_1 in Equation 4 are adjusted to a nominal set of test conditions (*Federal Register* 1998). Table 2 presents the nominal test conditions and permissible test condition ranges specified in the DOE water heater test procedure.

Overall Heat Loss Area Coefficient Measurements

The overall heat loss area coefficient is determined by performing an energy balance on the water heater yielding

$$Q_{in} = Q_1 + Q_{hw} + Q_{stored}. \qquad (5)$$

During tests to measure the overall heat loss area coefficient, no water is removed from the tank. The test is terminated when the storage tank temperature is equal to the initial storage tank temperature. Thus, Equation 5 reduces to

$$Q_{in} = Q_1, \qquad (6)$$

TABLE 2
Water Heater Test Conditions

Test Condition	Nominal Value	Permissible Variation
Daily hot water removal	243.4 L (64.3 gal)	±3.8 L (±1 gal)
Draw flow rate	11.4 L/min (3.0 gal/min)	±1.0 L/min (±0.25 gal/min)
Storage tank temperature	57.2°C (135.0°F)	±2.8°C (±5.0°F)
Supply water temperature	14.4°C (58°F)	±1.1°C (±2.0°F)
Ambient temperature	19.7°C (67.5°F)	±0.6°C (±2.5°F)

which may be expressed as

$$\int_0^{\tau} P_{in} d\tau = \int_0^{\tau} UA(T_t - T_a) d\tau \qquad (7)$$

or

$$UA = \frac{\int_0^{\tau} P_{in} d\tau}{\int_0^{\tau} (T_t - T_a) d\tau} \qquad (8)$$

where

UA = overall heat-loss-area coefficient, W/°C (Btu/°F·h);

P_{in} = power supplied to the storage tank, W (Btu/h);

T_t = average storage tank temperature, °C (°F);

T_a = ambient temperature surrounding the water heater, °C (°F);

τ = test duration, (h).

The heating elements within the storage tank were energized approximately 24 hours before the test was started. This ensured that the storage tank and water were in thermal equilibrium. Each test was conducted for five to seven days during which measurements were made every 10 minutes.

RESULTS

Measurements of Thermal Conductivity

Table 3 summarizes the test conditions and measured thermal conductivity for the polyurethane foam block specimens produced using the three blowing agents, R-141b, H_2O/CO_2, and R-245fa. As previously noted, the one-meter guarded hot plate apparatus was operated in the double-sided mode of operation. Thus, the thermal conductivity measurements represent the average of two specimens produced with each blowing agent.

Column 2 in Table 3 is the average thickness of the top and bottom specimens. The temperature, pressure, and relative humidity of the ambient air surrounding the specimens during

TABLE 3
Thermal Conductivity Measurements of Polyurethane Foams

Test	L_{avg}		T_a		P_a		RH	T_M		ΔT		λ	
	mm	in.	°C	°F	kPa	in. Hg	%	°C	°F	°C	°F	$\frac{W}{m \cdot K}$	$\frac{Btu \cdot in.}{h \cdot ft^2 °F}$
Blowing Agent HCFC-141b—Elapsed Time After Production: 27-29 days													
1	65.36	2.575	28.80	83.80	99.50	29.47	<10	28.80	83.80	18.10	32.60	0.0214	0.148
2	65.35	2.575	34.30	93.80	98.61	29.20	<10	34.30	93.80	29.20	52.60	0.0221	0.153
3	65.34	2.572	39.90	103.80	98.28	29.10	<10	39.90	103.80	40.30	72.50	0.0229	0.159
Blowing Agent H_2O/CO_2—Elapsed Time After Production: 27-29 days													
1	65.14	2.565	28.70	83.70	98.82	29.26	<10	28.80	83.80	18.10	32.60	0.0305	0.211
2	65.12	2.564	34.30	93.80	97.79	28.96	<10	34.30	93.80	29.20	52.60	0.0314	0.218
3	65.07	2.562	39.90	103.80	98.34	29.12	<10	39.90	103.80	40.30	72.50	0.0324	0.225
Blowing Agent HFC-245fa—Elapsed Time After Production: 26-29 days													
1	65.65	2.585	28.70	83.70	99.63	29.50	<10	28.80	83.80	18.10	32.60	0.0207	0.144
2	65.64	2.584	34.30	93.80	99.79	29.55	<10	34.30	93.80	29.20	52.60	0.0214	0.149
3	65.62	2.583	39.90	103.80	99.68	29.52	<10	39.90	103.80	40.30	72.50	0.0221	0.153

each test are tabulated in columns 3, 4, and 5 respectively. The mean temperature of the specimen and the temperature difference between the hot and cold sides of the specimen are listed in columns 6 and 7, respectively. The measured thermal conductivity for each set of specimens is listed in column 8.

The measurement uncertainties for thermal conductivity were derived in accordance with current ISO guidelines (Taylor and Kuyatt 1994; ISO 1993) consistent with previous results (Zarr 1997). The relative uncertainty ($k = 1$) for the estimates of thermal conductivity was 1.5%.

Thermal conductivity values are plotted in Figure 4 as a function of mean temperature. The conductivity of polyurethane foams produced using H_2O/CO_2 as the blowing agent was approximately 42% greater than the conductivity of foams produced using R-141b. The conductivity of polyurethane foams produced using R-245fa was approximately 3% lower than the conductivity of the polyurethane foams using the R-141b blowing agent.

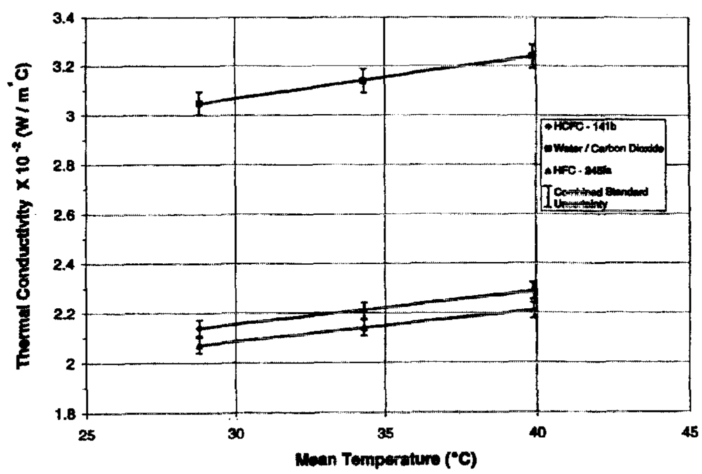

Figure 4 *Thermal conductivity of polyurethane foams versus mean specimen temperature.*

Energy Factor Measurements

The test conditions and measured energy factors for the four water heaters manufactured with R-141b, H_2O/CO_2, and R-245fa blowing agents are summarized in Tables 4, 5, and 6, respectively. A series of four to six 24-hour simulated use tests were conducted for each water heater. The tables include the average energy factor and standard deviations for the individual water heaters as well as the average and standard deviation for each group of four water heaters. The results for the first day of each test series were not included in the computation of the average energy factors or the standard deviations. During the first day the materials used in the water heater's construction may not be in thermal equilibrium with the stored water. This issue is addressed in DOE's *Test Procedures for Residential Water Heaters* (*Federal Register* 1998) by allowing the water heater's thermostats to cycle up to three times before a test commences.

The average energy factors for the four water heaters using R-141b as the blowing agent (Table 4) ranged from 0.885 to 0.892 with an average value of 0.887. The largest standard deviation between test results for a single tank, 19242-12-53-7, was 0.0016, whereas the standard deviation between tanks was 0.0028.

Table 5 summarizes the test results for the four tanks that were manufactured using H_2O/CO_2 as the blowing agent. The average energy factor for each of the water heaters within this

TABLE 4
Water Heater Energy Factor Measurements, Blowing Agent HCFC-141b

Test Day	Avg. Ambient °C (°F)	Avg. Inlet Temp. °C (°F)	Avg. Outlet Temp. °C (°F)	Daily Mass kg (lb)	Daily Load kJ (Btu)	Energy Factor
Tank Number: 19242-12-53-7						
05/12/98	19.46 (67.03)	14.87 (58.77)	58.54 (137.37)	239.54 (528.09)	43,706.47 (41,393.80)	0.869
05/13/98	19.47 (67.05)	14.86 (58.75)	58.54 (137.37)	239.88 (528.84)	43,787.55 (41,470.59)	0.887
05/14/98	19.43 (66.97)	14.83 (58.69)	58.51 (137.32)	239.96 (529.02)	43,796.88 (41,479.42)	0.886
05/15/98	19.47 (67.05)	14.83 (58.69)	58.77 (137.79)	239.81 (528.69)	44,032.11 (41,702.21)	0.883
05/16/98	19.49 (67.08)	14.81 (58.66)	58.66 (137.59)	240.18 (529.50)	44,012.96 (41,684.07)	0.887
Averages	**19.47 (67.04)**	**14.83 (58.70)**	**58.62 (137.52)**	**239.96 (529.01)**	**43,907.38 (41,584.07)**	**0.886**
Std. Dev.	**0.02 (0.04)**	**0.02 (0.03)**	**0.10 (0.19)**	**0.14 (0.31)**	**115.41 (109.30)**	**0.0016**
Tank Number: 19242-12-53-8						
05/07/98	19.53 (67.15)	14.83 (58.69)	59.07 (138.33)	239.59 (528.20)	44,288.17 (41,944.72)	0.869
05/08/98	19.50 (67.10)	14.84 (58.71)	58.06 (136.51)	241.27 (531.90)	43,581.36 (41,275.31)	0.887
05/09/98	19.50 (67.10)	14.82 (58.68)	57.59 (135.66)	238.82 (526.50)	42,687.30 (40,428.56)	0.884
05/10/98	19.51 (67.12)	14.83 (58.69)	57.39 (135.30)	239.07 (527.05)	42,517.21 (40,267.47)	0.884
Averages	**19.50 (67.11)**	**14.83 (58.69)**	**57.68 (135.82)**	**239.72 (528.49)**	**42,928.62 (40,657.11)**	**0.885**
Std. Dev.	**0.00 (0.01)**	**0.01 (0.01)**	**0.28 (0.51)**	**1.10 (2.43)**	**466.75 (442.05)**	**0.0014**
Tank Number: 19242-12-53-9						
05/01/98	19.52 (67.14)	14.84 (58.71)	58.61 (137.50)	242.84 (535.37)	44,406.27 (42,056.57)	0.855
05/02/98	19.45 (67.01)	14.84 (58.71)	57.79 (136.02)	242.38 (534.35)	43,504.82 (41,202.82)	0.886
05/03/98	19.48 (67.06)	14.83 (58.69)	57.43 (135.37)	241.57 (532.57)	43,011.69 (40,735.78)	0.884
05/04/98	19.50 (67.10)	14.85 (58.73)	57.31 (135.16)	241.59 (532.61)	42,868.09 (40,599.78)	0.886
05/05/98	19.46 (67.03)	14.85 (58.73)	57.23 (135.01)	241.10 (531.53)	42,708.83 (40,448.95)	0.886
Averages	**19.47 (67.05)**	**14.84 (58.72)**	**57.44 (135.39)**	**241.66 (532.76)**	**43,023.36 (40,746.83)**	**0.886**
Std. Dev.	**0.02 (0.03)**	**0.01 (0.01)**	**0.21 (0.39)**	**0.46 (1.01)**	**297.90 (282.14)**	**0.0009**
Tank Number: 19242-12-135.0053-10						
05/19/98	19.45 (67.01)	14.89 (58.80)	58.36 (137.05)	240.35 (529.88)	43,655.99 (41,135.99)	0.873
05/20/98	19.45 (67.01)	14.86 (58.75)	57.22 (135.00)	240.32 (529.81)	42,532.66 (40,282.10)	0.892
05/21/98	19.36 (66.85)	14.86 (58.75)	57.00 (134.60)	240.31 (529.79)	42,309.07 (40,070.34)	0.892
05/22/98	19.34 (66.81)	14.86 (58.75)	57.01 (134.62)	240.48 (530.16)	42,358.89 (40,117.52)	0.891
05/23/98	19.37 (66.87)	14.81 (58.66)	56.99 (134.58)	240.62 (530.47)	42,406.20 (40,162.33)	0.892
05/24/98	19.41 (66.94)	14.80 (58.64)	57.28 (135.10)	240.69 (530.63)	42,722.68 (40,462.06)	0.892
Averages	**19.39 (66.89)**	**14.84 (58.71)**	**57.10 (134.78)**	**240.48 (530.17)**	**42,465.90 (40,218.87)**	**0.892**
Std. Dev.	**0.04 (0.07)**	**0.03 (0.05)**	**0.12 (0.22)**	**0.15 (0.34)**	**148.33 (140.48)**	**0.0004**
Overall energy factor for all 4 tanks:			**Average = 0.887**			
			Standard Deviation: 0.0028			

TABLE 5
Water Heater Energy Factor Measurements, Blowing Agent H_2O/CO_2

Test Day	Avg. Ambient °C (°F)	Avg. Inlet Temp. °C (°F)	Avg. Outlet Temp. °C (°F)	Daily Mass kg (lb)	Daily Load kJ (Btu)	Energy Factor
Tank Number: 19242-12-86-67						
06/09/98	19.43 (66.97)	14.87 (58.77)	58.80 (137.84)	240.98 (531.26)	44,236.37 (41,895.66)	0.853
06/10/98	19.42 (66.96)	14.88 (58.78)	58.43 (137.17)	241.27 (531.90)	43,902.22 (41,579.19)	0.876
06/11/98	19.45 (67.01)	14.90 (58.82)	58.54 (137.37)	241.31 (531.99)	44,006.82 (41,678.26)	0.868
06/12/98	19.69 (67.44)	14.88 (58.78)	58.36 (137.05)	241.37 (532.12)	43,854.43 (41,533.93)	0.871
06/13/98	19.40 (66.92)	14.87 (58.77)	58.25 (136.85)	241.36 (532.10)	43,748.48 (41,433.59)	0.869
Averages	**19.49 (67.08)**	**14.88 (58.79)**	**58.40 (137.11)**	**241.33 (532.03)**	**43,877.99 (41,556.24)**	**0.871**
Std. Dev.	**0.12 (0.21)**	**0.01 (0.02)**	**0.11 (0.19)**	**0.04 (0.09)**	**92.89 (87.97)**	**0.0031**
Tank Number: 19242-12-86-7						
07/14/98	19.88 (67.78)	14.92 (58.86)	56.70 (134.06)	241.04 (531.40)	42,082.98 (39,856.21)	0.865
07/15/98	19.91 (67.84)	14.93 (58.87)	56.71 (134.08)	240.86 (531.00)	42,051.50 (39,826.40)	0.866
07/16/98	20.20 (68.36)	14.93 (58.87)	56.62 (133.92)	241.30 (531.97)	42,031.90 (39,807.84)	0.868
07/17/98	20.21 (68.38)	14.94 (58.89)	56.45 (133.61)	241.28 (531.93)	41,851.73 (39,637.20)	0.867
07/18/98	19.66 (67.39)	14.86 (58.75)	56.36 (133.45)	241.31 (531.99)	41,873.75 (39,629.64)	0.867
07/19/98	20.19 (68.34)	14.90 (58.82)	56.54 (133.77)	241.47 (532.34)	42,017.01 (39,793.73)	0.866
Averages	**20.03 (68.06)**	**14.91 (58.84)**	**56.54 (133.76)**	**241.24 (531.85)**	**41,959.18 (39,738.96)**	**0.867**
Std. Dev.	**0.22 (0.39)**	**0.03 (0.05)**	**0.12 (0.22)**	**0.20 (0.45)**	**91.68 (88.83)**	**0.0007**
Tank Number: 19242-12-86-8						
06/22/98	20.02 (68.04)	15.01 (59.02)	58.52 (137.34)	240.51 (530.23)	43,730.09 (41,416.17)	0.852
06/23/98	20.06 (68.11)	15.05 (59.09)	57.34 (135.21)	243.37 (532.12)	42,655.57 (40,398.51)	0.872
06/24/98	20.01 (68.02)	14.97 (58.95)	56.68 (134.02)	241.78 (533.03)	42,140.77 (39,910.95)	0.871
06/25/98	20.23 (68.41)	14.99 (58.98)	56.41 (133.54)	240.76 (530.78)	41,673.02 (39,467.95)	0.873
06/26/98	21.70 (71.06)	15.01 (59.02)	56.51 (133.72)	240.92 (531.13)	41,776.50 (39,565.95)	0.871
06/27/98	20.45 (68.81)	15.04 (59.07)	56.58 (133.84)	241.28 (531.93)	41,855.13 (39,668.83)	0.871
Averages	**20.49 (68.88)**	**15.01 (59.02)**	**56.70 (134.07)**	**241.22 (531.80)**	**42,026.20 (39,802.44)**	**0.872**
Std. Dev.	**0.62 (1.12)**	**0.03 (0.05)**	**0.33 (0.59)**	**0.36 (0.79)**	**351.06 (332.49)**	**0.0008**
Tank Number: 19242-12-86-9						
06/30/98	19.97 (67.95)	15.01 (59.02)	57.17 (134.91)	240.51 (530.23)	42,370.41 (40,128.43)	0.850
07/01/98	19.70 (67.46)	14.89 (58.08)	57.17 (134.91)	241.13 (531.60)	42,599.27 (40,345.18)	0.868
07/02/98	19.57 (67.23)	14.86 (58.75)	57.34 (135.21)	241.63 (532.70)	42,893.92 (40,624.24)	0.868
07/03/98	19.83 (67.69)	14.86 (58.75)	57.34 (135.21)	241.76 (532.98)	42,917.23 (40,646.32)	0.867
07/04/98	19.83 (67.69)	14.87 (58.77)	57.20 (134.96)	242.15 (533.84)	42,840.43 (40,573.58)	0.868
Averages	**19.73 (67.52)**	**14.87 (58.77)**	**57.26 (135.07)**	**241.67 (532.78)**	**42,812.71 (40,547.33)**	**0.868**
Std. Dev.	**0.11 (0.19)**	**0.01 (0.02)**	**0.08 (0.14)**	**0.36 (0.80)**	**126.34 (119.65)**	**0.0004**
Overall energy factor for all 4 tanks:			**Average = 0.870**			
			Standard Deviation: 0.0021			

TABLE 6
Water Heater Energy Factor Measurements, Blowing Agent HFC-245fa

Test Day	Avg. Ambient °C (°F)	Avg. Inlet Temp. °C (°F)	Avg. Outlet Temp. °C (°F)	Daily Mass kg (lb)	Daily Load kJ (Btu)	Energy Factor
Tank Number: 19242-12-109-12						
07/20/98	20.26 (68.47)	14.86 (58.75)	58.52 (137.34)	241.94 (533.38)	44,130.31 (41,795.21)	0.875
07/21/98	20.80 (69.44)	14.93 (58.87)	57.72 (135.90)	241.68 (532.81)	43,208.27 (40,921.96)	0.885
07/22/98	20.48 (68.86)	14.96 (58.93)	57.27 (135.09)	241.70 (532.85)	42,733.13 (40,471.96)	0.884
07/23/98	20.28 (68.50)	14.97 (58.95)	56.98 (134.56)	241.57 (532.57)	42,402.63 (40,158.95)	0.885
Averages	**20.52 (68.94)**	**14.95 (58.92)**	**57.32 (135.18)**	**241.65 (532.74)**	**42,781.34 (40,517.62)**	**0.885**
Std. Dev.	**0.21 (0.39)**	**0.02 (0.03)**	**0.30 (0.55)**	**0.06 (0.13)**	**330.66 (313.17)**	**0.0005**
Tank Number: 19242-12-109-8						
07/24/98	19.59 (67.26)	15.10 (59.18)	56.88 (134.38)	241.11 (531.55)	42,095.77 (39,868.33)	0.867
07/27/98	19.67 (67.41)	14.92 (58.86)	55.83 (132.49)	240.90 (531.09)	41,181.92 (39,002.83)	0.883
07/28/98	19.94 (67.89)	14.95 (58.91)	56.07 (132.93)	241.24 (531.84)	41,460.41 (39,266.59)	0.880
07/29/98	19.96 (67.93)	14.93 (58.87)	56.06 (132.91)	241.45 (532.30)	41,496.80 (39,301.05)	0.881
07/30/98	20.07 (68.13)	14.92 (58.86)	55.96 (132.73)	241.44 (532.28)	41,405.61 (39,214.69)	0.881
Averages	**19.91 (67.84)**	**14.93 (58.87)**	**55.98 (132.76)**	**241.26 (531.88)**	**41,386.19 (39,196.29)**	**0.881**
Std. Dev.	**0.15 (0.26)**	**0.01 (0.02)**	**0.10 (0.17)**	**0.22 (0.49)**	**122.32 (115.85)**	**0.0011**
Tank Number: 19242-12-109-9						
08/05/98	19.75 (67.55)	14.91 (58.84)	58.08 (136.54)	241.65 (532.74)	43,592.87 (41,286.21)	0.878
08/06/98	19.87 (67.77)	14.94 (58.89)	57.87 (136.17)	241.59 (532.61)	43,344.57 (41,051.05)	0.882
08/07/98	20.23 (68.41)	14.97 (58.95)	57.27 (135.09)	241.36 (532.10)	42,666.41 (40,408.77)	0.885
08/08/98	20.21 (68.38)	14.89 (58.80)	57.21 (134.98)	241.80 (533.07)	42,751.38 (40,489.28)	0.889
08/09/98	20.37 (68.67)	14.89 (58.80)	57.55 (135.59)	241.97 (533.45)	43,135.43 (40,852.97)	0.886
08/10/98	20.59 (69.06)	15.00 (59.00)	57.55 (135.59)	241.43 (532.26)	42,930.48 (40,658.87)	0.887
Averages	**20.25 (68.46)**	**14.94 (58.89)**	**57.49 (135.48)**	**241.63 (532.70)**	**42,965.65 (40,692.18)**	**0.886**
Std. Dev.	**0.24 (0.42)**	**0.04 (0.08)**	**0.24 (0.42)**	**0.23 (0.50)**	**248.64 (235.48)**	**0.0023**
Tank Number: 19242-12-109-11						
08/11/98	20.39 (68.70)	15.03 (59.05)	56.82 (134.28)	241.48 (532.37)	42,168.79 (39,937.48)	0.865
08/12/98	20.02 (68.04)	14.91 (58.84)	56.22 (133.20)	241.54 (532.50)	41,701.64 (39,495.05)	0.886
08/13/98	20.11 (68.20)	14.89 (58.80)	56.02 (132.84)	241.39 (532.17)	41,489.19 (39,293.84)	0.885
08/14/98	20.14 (68.25)	14.88 (58.78)	55.95 (132.71)	241.64 (532.72)	41,470.55 (39,276.19)	0.885
08/15/98	20.06 (68.11)	14.84 (58.71)	55.82 (132.48)	241.82 (533.12)	41,414.09 (39,222.72)	0.885
08/16/98	20.25 (68.45)	14.84 (58.71)	55.71 (132.28)	242.00 (533.51)	41,331.71 (39,144.70)	0.885
Averages	**20.12 (68.21)**	**14.87 (58.77)**	**55.94 (132.70)**	**241.68 (532.80)**	**41,481.44 (39,286.50)**	**0.885**
Std. Dev.	**0.08 (0.14)**	**0.03 (0.05)**	**0.17 (0.31)**	**0.21 (0.47)**	**122.98 (116.47)**	**0.0004**

Overall energy factor for all 4 tanks:	**Average = 0.884**
	Standard Deviation: 0.0018

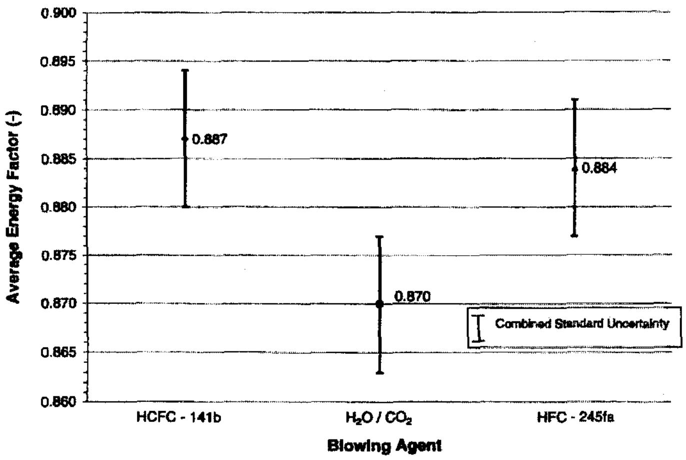

Figure 5 *Average energy factor and measurement uncertainty for water heaters produced using each foam blowing agent.*

group ranged from 0.867 to 0.872. The largest standard deviation associated with the tests conducted on a single water heater, 19242-12-86-6, was 0.0031. The average energy factor for the four water heaters using H_2O/CO_2 as the blowing agent is 0.870 with an associated standard deviation of 0.0021.

The test results associated with the third series of water heaters, manufactured using the R-245fa blowing agent, are summarized in Table 6. The average energy factor for the four water heaters tested ranged from 0.881 to 0.886 with an average energy factor of 0.884. The largest variability in test results was for water heater 19242-12-109-9, where the energy factor varied from 0.882 to 0.889, resulting in a standard deviation of 0.0023. The standard deviation associated with the average energy factor for the four tanks within this group was 0.0018.

The measurement uncertainty associated with the energy factor measurements were derived in accordance with ISO guidelines (ISO 1993). The relative uncertainty ($k = 1$) for the energy factor measurements is 0.8%.

Figure 5 shows the average energy factor for each set of four tanks and the uncertainty associated with each value. These results show that the average energy factor for water heaters manufactured using R-141b as the blowing agent was slightly higher, 0.887 versus 0.884, than the energy factor for the water heaters that utilized R-245fa as the blowing agent. The 0.870 average energy factor for the four tanks manufactured using H_2O/CO_2 is 0.017 (1.9%) and 0.014 (1.6%) lower than the average energy factors measured for the water heaters manufactured using the R-141b and R-245fa blowing agents, respectively.

The difference between the average energy factors measured for water heaters manufactured using blowing agents R-141b and R-245fa is within the experimental uncertainty. However, the average energy factor for the water heaters manufactured using the H_2O/CO_2 blowing agent is statistically different and is less than the energy factors obtained using the other two blowing agents.

Overall Heat Loss Area Coefficient Measurements

The overall heat loss area coefficient for each water heater is given in Table 7. For water heaters manufactured using the R-141b blowing agent, the average overall heat loss area coefficient is 1.46 W/°C (3.11 Btu/°F·h). The average coefficient for water heaters manufactured with R-245fa was 1.48 W/°C (3.14 Btu/°F·h), or 1.3% greater. The average coefficient for water heaters manufactured with the H_2O/CO_2 blowing agent is 1.77 W/°C (3.76 Btu/°F·h) or 21% and 20%, respectively, greater than the average heat loss coefficient for water heaters produced using R-141b and R-245fa blowing agents. The relative uncertainty associated with the overall heat loss area coefficients (4, 5) is 1.2%.

DISCUSSION

It is interesting to note that although the average overall heat loss area coefficient for water heaters that utilized the H_2O/CO_2 blowing agent was 21% higher than that for the tanks that used the R-141b blowing agent, 1.77 W/°C versus 1.46 W/°C, the average energy factor was only 1.9% lower (0.870 versus 0.887). The following analysis further explores the relationship between a water heater's overall heat loss area coefficient and energy factor.

Assuming that there is no change in the stored energy during the 24-hour simulated use test, Equation 4 may be rearranged to yield

$$\eta_{th} = \frac{Q_{hw}}{\dfrac{Q_{hw} + Q_l}{\eta_r}}. \tag{9}$$

Furthermore, assuming that the test conditions are at nominal test conditions (*Federal Register* 1998), rearrangement of Equation 9 gives the water heater's energy factor:

$$EF = \frac{\eta_r}{1 + \dfrac{Q_l}{Q_{hw}}}. \tag{10}$$

Expressing the heat loss from the tank as a function of the overall heat loss area yields

$$Q_l = UA\,(T_t - T_a)\,\tau. \tag{11}$$

The relationship between the overall heat loss area coefficient and energy factor can be examined by combining Equations 10 and 11, yielding

$$EF = \frac{\eta_r}{1 + \dfrac{UA(T_t - T_a)\tau}{Q_{hw}}}. \tag{12}$$

Using the values of recovery efficiency, hot water load, average tank temperature, and ambient temperature specified

TABLE 7
Overall Heat Loss Area Coefficients

Tank Number	Blowing Agent	Overall Heat Loss Area Coefficient						
		Measured		Computer–*UA*		Thermal Anomalies–UA_p		Thermal Anomalies/Measured
		W/°C	Btu/°F·h	W/°C	Btu/°F·h	W/°C	Btu/°F·h	%
19242-12-53-7	HCFC-141b	1.39	2.96	0.93	1.98	0.46	0.98	33.0
19242-12-53-8	HCFC-141b	1.55	3.30	0.93	1.98	0.62	1.32	40.0
19242-12-53-9	HCFC-141b	1.48	3.15	0.93	1.98	0.55	1.17	37.0
19242-12-53-10	HCFC-141b	1.40	2.98	0.93	1.98	0.47	1.00	34.0
AVERAGE		**1.46**	**3.11**	**0.93**	**1.98**	**0.53**	**1.12**	**36.0**
19242-12-86-6	H_2O/CO_2	1.87	3.98	1.24	2.64	0.63	1.34	34.0
19242-12-86-7	H_2O/CO_2	1.75	3.73	1.24	2.64	0.51	1.09	29.0
19242-12-86-8	H_2O/CO_2	1.75	3.73	1.24	2.64	0.51	1.09	29.0
19242-12-86-9	H_2O/CO_2	1.69	3.60	1.24	2.64	0.45	0.96	27.0
AVERAGE		**1.77**	**3.76**	**1.24**	**2.64**	**0.53**	**1.12**	**30.0**
19242-12-109-12	HFC-245fa	1.44	3.07	0.92	1.96	0.52	1.11	36.0
19242-12-109-8	HFC-245fa	1.53	3.26	0.92	1.96	0.61	1.30	40.0
19242-12-109-9	HFC-245fa	1.53	3.26	0.92	1.96	0.61	1.30	40.0
19242-12-109-11	HFC-245fa	1.40	2.98	0.92	1.96	0.48	1.02	34.0
AVERAGE		**1.48**	**3.14**	**0.92**	**1.96**	**0.56**	**1.18**	**38.0**

in the DOE test procedure (*Federal Register* 1998), as the overall heat loss area coefficient is doubled from 1.05 W/°C to 2.11 W/°C (2.0 Btu/°F to 4.0 Btu/°F·h), the energy factor decreases from 0.914 to 0.855, or approximately 7%. The functional relationship between the energy factor and overall heat loss area coefficient shown in Figure 6 may be expressed as

$$EF = 0.979 - 0.067UA + 0.003UA^2. \qquad (13)$$

Varying the overall heat loss area coefficient, *UA*, in Equation 13 by 21% results in a 2% variation in the energy factor. This result is consistent with the experimental measurements.

The relationship between the thermal conductivity of the insulation materials and the overall heat loss area coefficient was also explored. The overall heat loss area coefficient for a water heater without thermal anomalies, such as piping penetrations, may be expressed as

$$UA = (\lambda_t/L_t)\,A_t + (\lambda_b/L_b)\,A_b + (\lambda_s/L_s)\,A_s \qquad (14)$$

where

λ = thermal conductivity of the insulation, W/m °C (Btu · in./h · ft²·°F);

L = insulation thickness, m (in.);

A = surface area, $m^2(ft^2)$;

$_{t}$, $_{b}$, and $_{s}$ = location of the insulation material relative to the storage tank as top, bottom, and side.

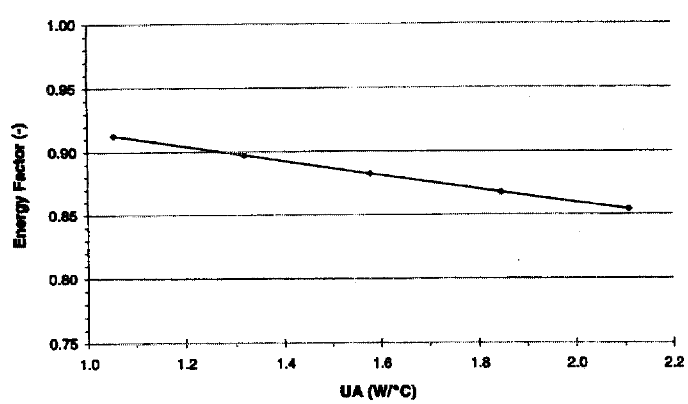

Figure 6 *Energy factor versus overall heat-loss area coefficient.*

Using the measured dimensions of the water heater, assuming a one-inch layer of glass-fiber insulation is located at the storage tank's bottom and a two-inch layer of polyurethane foam surrounds the remaining area of the storage tank, the overall heat loss area coefficients were computed (Table 7).

In addition to the heat conducted through the insulation, the heat loss from the water stored in the water heater is the result of thermal losses associated with piping penetrations and thermal shortcircuits that may exist between the storage tank and surrounding jacket. Thus, the overall heat loss area coefficient may be expressed as

$$UA = UA_i + UA_p \quad (15)$$

where

UA_i = overall heat loss area coefficient associated with the insulation surrounding the storage tank, W/°C (Btu/°F·h);

UA_p = heat loss attributed to piping penetrations, thermal shortcircuits, and variations in the nominal insulation thickness assumed in Equation 14, W/°C (Btu/°F·h).

The values of UA_p, Table 7, were computed by subtracting the overall heat loss area coefficient associated with the insulation, Equation 14, from the measured values. The relative importance of the thermal losses associated with piping penetrations and other thermal shortcircuits may be examined by comparing the computed and measured overall heat loss area coefficients in Table 7.

The average heat loss attributable to thermal anomalies, expressed as a percentage of the total, for water heaters manufactured using R-141b and R-245fa are essentially the same, 36% and 38% respectively. Thermal anomalies accounted for only 30% of the heat loss from the water heaters manufactured with H_2O/CO_2 as the blowing agent. This finding is consistent with Equation 15. As the thermal conductivity of the foam insulating material increases, the overall heat loss area coefficient associated with the insulation, UA_i in Equation 15, increases, resulting in a lower percentage of the total heat loss being attributable to thermal anomalies.

Examples of thermal shortcircuits are readily identified using infrared thermography (Figure 7). This image shows significant temperature elevations associated with the piping penetrations, the heating element access covers, and the water heater's lower perimeter.

CONCLUSIONS

Polyurethane foams were manufactured using three blowing agents, R-141b, H_2O/CO_2, and R-245fa. The foams were produced in block form for thermal conductivity measurements and as insulation used in the construction of residential electric water heaters. The thermal conductivity of the foam specimens was measured using a one-meter guarded hot plate apparatus at three mean temperatures by maintaining the cold plate at 19.7°C (67.5°F) and operating the hot plate at nominal temperatures of 51.7°C (125°F), 57.2°C (135°F), and 62.8°C (145°F). The thermal conductivity of the polyurethane foam specimens produced using R-141b, the blowing agent currently used by water heater manufacturers, at a mean temperature of 34.3°C (66.3°F), is 0.0221 W/m·K. At identical measurement conditions, the thermal conductivity of the specimens produced using R-245fa and H_2O/CO_2 were measured to be 0.0214 W/m·K and 0.0314 W/m·K, respectively. The thermal conductivity of the foam specimens increased linearly with the specimen's mean temperature.

Three sets of four water heaters were insulated with each of the three polyurethane insulation materials. The energy factor and overall heat loss area coefficient were measured for each of the 12 water heaters. The 24-hour simulated use test, used to determine the energy factor, was repeated up to seven times for an individual water heater to access the test procedure's repeatability. The average energy factor for the four water heaters manufactured with the blowing agent R-141b was 0.887. Use of the R-245fa blowing agent resulted in an average energy factor of 0.884. Water heaters insulated with H_2O/CO_2 based polyurethane foam resulted in an average energy factor of 0.870. The uncertainty associated with the energy factor measurements is 0.007.

The overall heat loss area coefficient quantifies the thermal integrity of a water heater. It includes heat loss through the insulation surrounding the storage tank as well as heat conducted through piping penetrations and other thermal shunts. Tests were conducted on each of the water heaters to measure its overall heat loss area coefficient. The

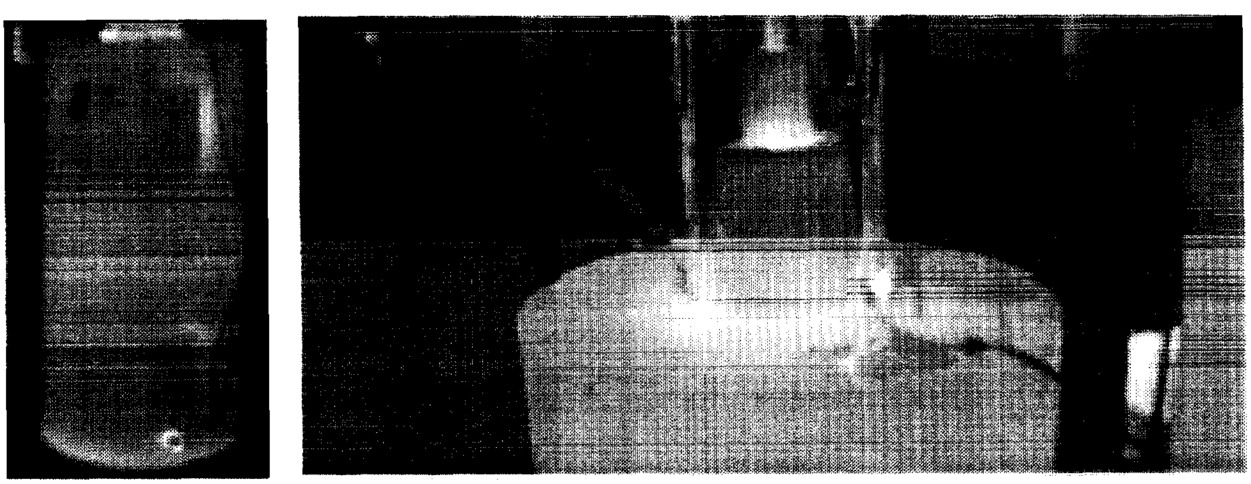

Figure 7 *Infrared image of front (left) and top (right) of residential electric water heater.*

average overall heat loss area coefficients for the four water heaters manufactured using R-141b, R-245fa, and H_2O/CO_2 blown polyurethane foams are, respectively, 1.46 W/°C (3.11 Btu/°F·h), 1.48 W/°C (3.14 Btu/°F·h), and 1.77 W/°C (3.76 Btu/°F·h). The measurement uncertainty associated with the overall heat loss coefficient measurements is 0.02 W/°C (0.03 Btu/°F·h). Calculations determined the fraction of the total heat loss attributed to the piping penetrations and thermal shunts, which was approximately 38%. The fraction of heat loss through the thermal insulation is approximately 62%. Infrared images of the water heaters revealed significant heat losses around the bottom perimeter of the storage tank, the heating element access covers, and the piping penetrations.

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